Understanding Apex Predator and Pelagic Fish Habitat Utilization in the California Current System by Integrating Animal Tracking with in situ Oceanographic Observations

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LONG-TERM GOALS

The long-term goals of this program are to map the oceanic habitats used by top predators in the California Current System (CCS) and broader Pacific Ocean and to characterize the environmental features that define these hotspot regions. This will be done by examining both top down and bottom up processes, and predicting how climate variability impacts the distribution and utilization of oceanic habitats by top predators. We are also developing methods that are required to integrate animal collected data into existing oceanographic databases. To achieve these goals, we have assembled a team that includes researchers from the University of California Santa Cruz (UCSC) and Stanford's Hopkins Marine Station and oceanographers from the Environmental Research Division (ERD), a branch of National Marine Fisheries Service (NMFS) in Pacific Grove. The integration and analysis of the diverse datasets requires the development of new software which is being developed collaboratively by the NMFS, UCSC, and Stanford as well as researchers from Sea Mammal Research Unit (SMRU) in Scotland.

OBJECTIVES

Develop a dynamic, ecosystem-based approach to map and understand habitat utilization by top marine predators in the Pacific Ocean, with an emphasis on the CCS. Specifically:

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(1) To map critical habitat of a variety of to predator species;

(2) To link the distribution and movement patterns of these predators to physical and biological ocean features, in order to:

a. determine how ocean dynamics act to aggregate diverse organisms;
b. define the stability and community structure around biological hot spots;
c. define the persistence of hot spots in space and time;
d. examine the relationships among different species in the context of habitat utilization;
e. identify the influence of top down and bottom up processes and their influence on dynamics of hot spots;

(3) To map habitat distribution of commercially-viable and threatened fish stocks in the CCS, based on predator distribution and behavior from tracking data;

(4) To quantify the seasonal and interannual variability of mesoscale ocean features (potential hot spots), from remotely sensed and *in situ* data;

(5) To contribute a significant quantity of high-resolution *in situ* oceanographic data from animal tags to coastal and global ocean observing programs;

(6) To provide critical advice to fisheries managers on the distribution of commercially-viable fish stocks in relation to oceanographic variability;

(7) To develop and test models that allow for the prediction of animal abundance and distribution based on the physical environment.

APPROACH

Oceanographic data have been obtained from both satellite imagery and the electronic tags deployed on top predators, which record environmental variables such as temperature, depth, light and salinity. Physical data obtained by tagged animals permits comparison to features that are spatially and temporally concurrent with the animals' foraging behavior. For example, temperature and salinity data collected by the tags will place the animals' behavior in the context of distinct water mass properties. Large-scale habitat usage is being modeled based on individual animal utilization. Habitat preference is indicated when an animal uses an area more than would be expected based on relative availability of habitat. Our approach to define habitat usage starts by modeling the relative accessibility of habitat mechanistically based on distance from a capture site, speed of movement, residency patterns, and the observed distribution of trip durations. These estimates are then used as variables within a variety of modeling approaches to relate the environmental variables that define habitats and spatial utilization by tagged animals.

One of the critical requirements in ecosystem-based resource management is learning how to define zones of high biological activity, or "biological hot spots". How best to characterize these "hot spots", whether determination is based on how animals use the habitat (behavioral changes), or how to quantify their temporal variability, stability and long-term viability, remains unknown. Regardless, the first step is to identify where and when they occur. The Tagging of Pacific Pelagics (TOPP) research program, which is composed of the member groups listed above, is providing new data on spatial and

temporal characteristics of hot spots in the CCS as well as new methods to identify them using both remotely sensed oceanographic information and data obtained from the tagged animals.

In the first phase of the NOPP grant, our focus was on automating routines that allow more rapid assessment and integration of animal collected and remotely sensed data to evaluate the habitat utilized by the tagged animals in relation to the surrounding oceanography. This has occurred in two phases. Our initial emphasis was on delivery of tag derived data to a Live Access Server (LAS), which involved development of database code and data delivery in a seamless fashion from multiple archival tag sources. Secondly, data visualization software was developed for both fish and marine mammal derived datasets. The fish research team intends to combine visualization and data analysis software developed from independent laboratories (e.g. Block lab) into one software package that can integrate ongoing TOPP funded efforts in the marine mammal area (Costa and Fedak labs). To accomplish this, the development of code specific to the complexities of diving fish, as well as air-breathing mammals, is required.

WORK COMPLETED

Cumulatively, our program has deployed 3,647 tags on 2,771 individual animals from 23 different species since 2002 (Figure 1). Nearly half of these species visit the California Current region for weeks to months or longer, indicating that the CCS is one of the most significant hotspots studied by our research program. We base this observation on the number of species and the abundance of tagged individuals that utilize this region of the North Pacific (Figure 2). We have defined at least three hotspots within the CCS: 1) the Monterey Bay and Gulf of the Farallones Marine Sanctuaries, 2) the Southern California Bight, and 3) the Baja Peninsula hot spots. We are now correlating the animal distributions with the oceanographic factors that define these hotspots and are beginning to construct models that explain the observed distributions for some species. This research has had an impact on the biologging and oceanographic communities, as evidenced by more than 30 publications in top-tier journals since 2006 that were directly or indirectly supported by this award (see publications listed at the end).

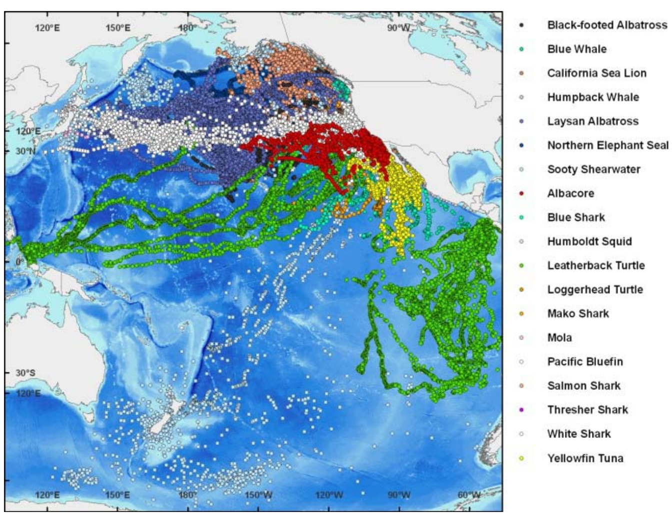

Figure 1. Dots show positions for 19 TOPP species.

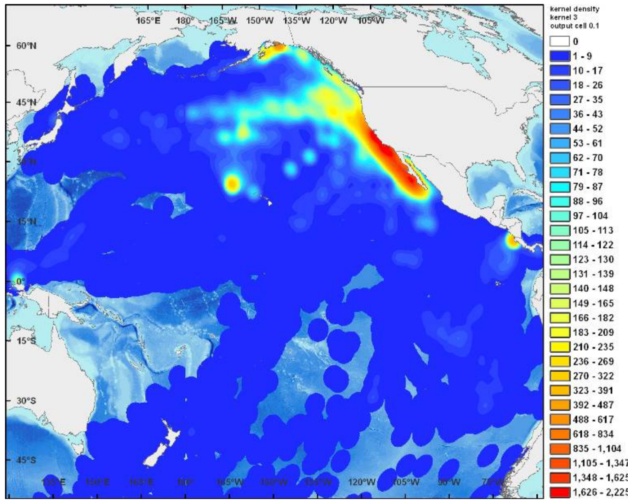

Figure 2. Kernel density plot of data presented above

Efforts to improve our understanding of the movements and distribution of top predators in relation to environmental variability in the Pacific Ocean yielded significant findings for three endangered species: the leatherback turtle (*Dermochelys coriacea*), the humpback whale (*Megaptera novaeangliae*), and the blue whale (*Balaenoptera musculus*). By assembling large teams and using a multidisciplinary approach, we were able to unravel the environmental factors shaping the migration pathway of eastern Pacific leatherback turtles, from their nesting beach in Costa Rica to their foraging ground in the South Pacific Gyre. Similarly, we used recent data from surveys at sea in combination with historical information to determine the influence of physical oceanography on the migratory destinations and distribution patterns of humpback and blue whales in the South Pacific. These studies have conservation applications to other species, and on a global scale.

RESULTS

Maps showing the kernel densities derived from the complete tracking data set (Figure 2) reveal both the wide distribution of our tagged animals as well as the aggregation of individuals and multiple species within particular oceanic regions. The CCS is clearly a hot spot for a number of these species, including those that were tagged far from the CCS (e.g., leatherback turtles, salmon sharks, black-footed albatross; see Figure 1). A focus of our research, therefore, has concentrated on the CCS. However, we can identify four other regions with elevated kernel densities, suggesting that they are important hot spots for specific or multiple species within our tagged community. These features are marked on the kernel density map (Figure 2) and are defined briefly below:

(1) North Pacific Transition Zone: This region separates the relatively oligotrophic waters of the Subtropical Gyre from the more productive and seasonally varyiable waters of the Subarctic Gyre. This region is characterized by strong frontal features, most importantly the Transition Zone Chlorophyll Front (Polovina et al., 2001; Bograd et al., 2004). The mesoscale structure and physical processes associated with this region tends to aggregate prey, and is therefore an important foraging hot spot for a number of species.

(2) Mesoscale Eddies: Large, long-lived eddies comprise another physical environment that is utilized by a variety of species, most prominently elephant seals and albatrosses. Anticyclonic eddies that are formed in coastal regions of the eastern Gulf of Alaska propagate offshore, carrying with them waters characteristic of the productive coastal regions. This offshore transport of biogenic material, combined with physical processes that aggregate prey along the edges, make eddies important "oases" of foraging potential in an otherwise patchy prey environment. These hot spots are dynamic and intermittent in space and time, but appear to be utilized by animals that are capable of long migrations.

(3) White Shark Café: This region, located mid-way between San Diego and Hawaii, was perhaps the most surprising of all the identified hot spots, as it occurs in a relatively quiescent portion of the Northeast Pacific and does not appear to be associated with any specific physical features. This region is persistently used by white sharks, which occupy this area for extended periods and undertake very different dive patterns than in other occupied regions to the northeast and southwest.

(4) South Pacific Subtropical Gyre: This region is a very different type of hot spot from those identified in the North Pacific. This region is targeted by only one of the tagged species, leatherback turtles that nest on the beaches of Costa Rica, and is highly unusual in being characterized by relatively low productivity. We have identified this region as an extremely important area for the critically endangered leatherbacks, which must find sufficient prey in this oligotrophic region to build reserves for subsequent nesting activities.

We use specific examples to characterize the identified hot spots and to describe how the animals are utilizing these environments:

<u>North Pacific Transition Zone</u>: Albatrosses breeding sympatrically in the northwest Hawaiian Islands forage extensively within the NPTZ (Kappes et al., in review). To date, TOPP researchers have tracked 300+ albatrosses over 6 consecutive seasons and the data reveal that Laysan albatrosses forage on the cooler northern edge of the NPTZ, whereas black-footed albatrosses forage on the warmer southern edge of the NPTZ (Figure 3). The habitat partitioning is consistent across multiple years suggesting distinct habitat and/or prey requirements for each species.

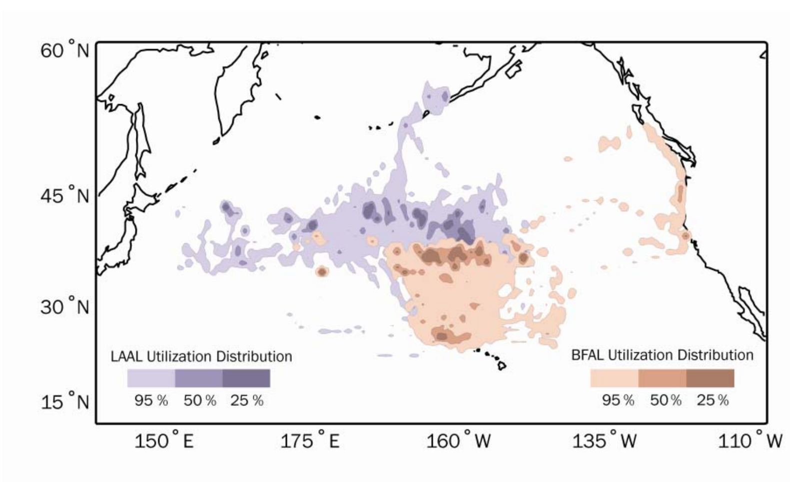

Figure 3. Kernal density distributions of Laysan (blue) and Black-footed (red) albatross tagged on Tern Island.

Mesoscale Eddies: Several years of vertical temperature profile data collected from tagged elephant seals provide an extensive data set to investigate eddies in the Gulf of Alaska. Preliminary results of the analysis of 130 elephant seal tracks over 6 years (2002-07) show that 21% of the trips included more than 10% of the time in eddies. Horizontal and vertical movements of the animals change within these features, suggesting enhanced foraging effort. Temperature data from these frequent and deep-diving (~500-800 m) elephant seals allow calculations of heat content anomalies associated with the eddies. In addition, the e-seals provide a unique data set of high-quality, high-resolution profile data with which to explore the structure and evolution of mesoscale features. The large number of e-seal tracks, combined with a tendency for some track fidelity, make it possible to sample individual eddies at different phases of their life cycle.

California Current System: As shown above, the CCS is the most prominent hot spot identified in our data set. The critical importance of this region is evident from the large number of animals that utilize this habitat (Figure 4). This is partly a result of tagging effort, which was focused within the CCS for a number of species (tuna, California sea lions, elephant seals, blue whales). However, animals tagged as far away as New Zealand (Shaffer et al., 2006) spent months within the CCS, indicating the importance of this region as a foraging hot spot for long distance migrants.

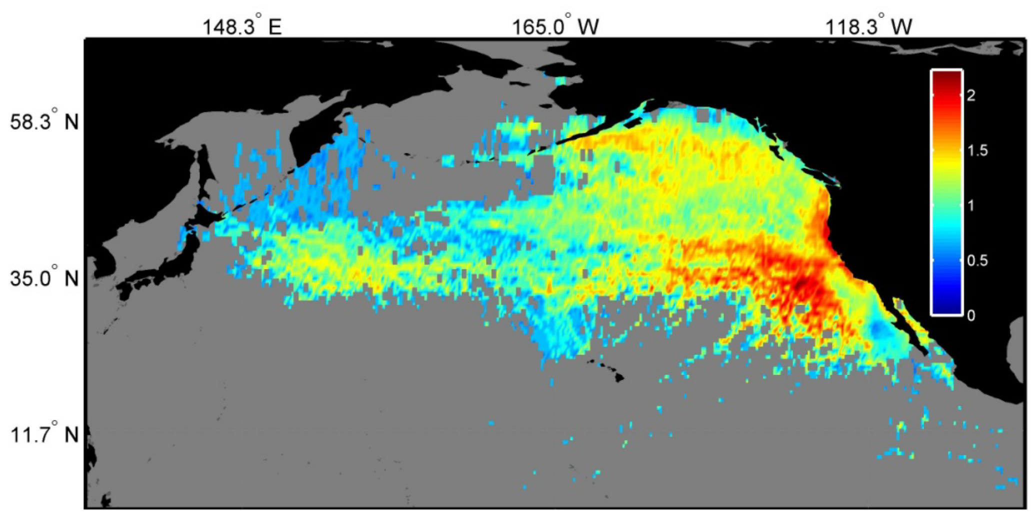

Figure 4. A spatial representation of the Shannon biodiversity index for 1519 tracks represent ting 18 TOPP species.

Given the large number of species studied in our research program, we have chosen to highlight the results of tagging studies on the bluefin tuna (*Thunnus orientalis*), which has been extensively tagged and has been found to heavily rely on the CCS. Building on the tracking studies of migrating Pacific bluefin tuna along the California coast by Boustany *et al.* (submitted) and Kitigawa *et al.* (2007), we are currently investigating two hotspot regions in the CCS that consistently attract large numbers of Pacific bluefin tuna during spring and summer seasons. Integrating track data from archival tags with tag measurements of water temperature and satellite remote sensing observations, we are attempting to identify the biological and physical features underlying these high use regions.

Habitat utilization distributions derived from kernel density analyses of daily geolocations were used to identify and delineate hotspot regions occupied by Pacific bluefin tuna off southern Baja in April-June and in the California Bight in July-August, 2004 (Figure 5). Analyses of satellite observations of sea surface temperature and chlorophyll-a concentration in each hot spot before, during, and after the time of occupancy by the fish suggest that the arrival and departure of fish into and out of these hotspot regions represents a balance between temperature preferences and ecosystem productivity. More specifically, the southern Baja hotspot is occupied when water temperatures are within the bluefin's physiological optimal range and productivity there is maximal, and then is vacated for the California Bight hot spot as water temperatures warm above 20°C. The bluefin tuna then leave this area and move into the much more productive waters farther north as temperatures at these northern latitudes reach their annual maximum. Ongoing analyses are examining the depth preferences and diving and feeding behavior of the fish both inside and outside of these hot spot regions, in order to gain further insight into the mechanistic processes that attract tuna to these regions and to infer the likely prey sources.

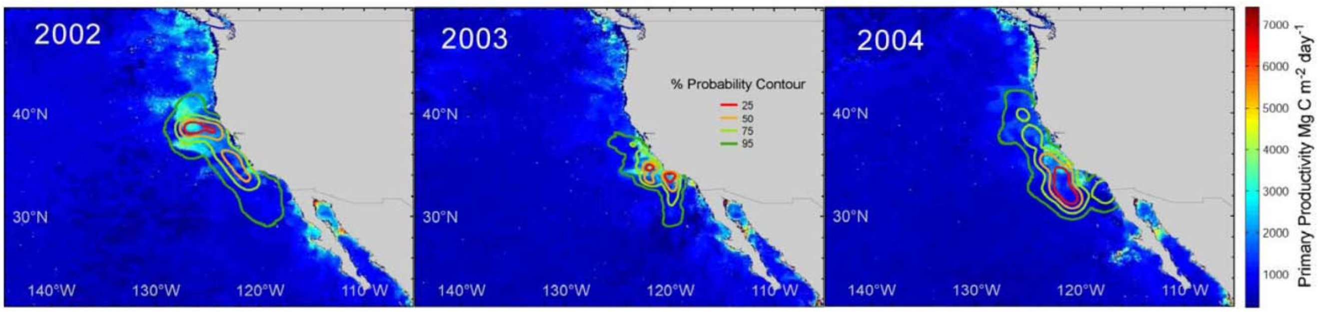

Figure 5. Utilization distributions of Pacific bluefin tuna tagged with archival tags in July of 2002 and 2003. Hotspots were defined via the 50% utilization contour. Left-hand panel shows the tuna's distribution during June 2004, at which time a hotspot was evident off Magdalena Bay in southern Baja. Right-hand panel shows the distribution during August 2004, by which time the tuna had shifted northwards to a hotspot region in the California Bight.

IMPACT/APPLICATIONS

Our ability to identify oceanic hotspots used by marine predators has significant implications for fisheries management and conservation. For example, areas that are deemed "sensitive" or critical to the proliferation of a given species could be protected or managed. However, because the oceans are so dynamic, it is important to identify key features or consistent phenomena (e.g. coastal upwelling or other physical forcing) that affect ocean productivity and the aggregation of predators and prey. This project has made significant progress towards understanding highly dynamic regions of the Pacific Ocean and the top predators that occur there.

TRANSITIONS

In addition to our contribution to biologging science in general, our research program (i.e. TOPP) has been at the forefront of tag development. Many new generation tags have been developed through collaborative efforts between TOPP researchers and industrial engineers. This includes the development of GPS and CTD tags that are now commercially available. We are also starting a new

collaboration with Lotek Wireless, who produces light-based archival tags that we deploy on a variety of species. The main effort will be to test new algrorithms that will improve the location quality (i.e. reduce error) of archival tags and the future development of Application Specific Integrated Circuits (ASIC) based tags with the hope that these tags can be used to track salmon along the California Coast. Another transitional effort will be the development of predictive models that we will test with data from new tag deployments. The thrust of this effort will create a model based on environmental variables that predicts animal distributions within the CCS. The model will be tested by conducting new tag deployments and determining if the newly tagged animals distribute themselves according to the predictions of our model. This will be a significant step because the models developed could be used by wildlife managers to more effectively manage protected resources. This model should be a defining legacy of the TOPP program and this grant.

SCIENCE EDUCATION AND COMMUNICATION

The NOPP award has directly supported 4 postdoctoral researchers, 6 Ph.D. student theses, and several technicians. The results of this research are communicated to the public on the TOPP web page, http://www.topp.org, which has undergone extensive revision with new flash mutlimedia content and blogging by the scientists. The web traffic has increased substantially.

RELATED PROJECTS

This project is closely linked to the Tagging of Pacific Pelagics program (TOPP) which is a pilot project of the Census of Marine Life (http://www.toppcensus.org). All the electronic tagging data for the project will be obtained from animals deployed as a part of the TOPP program. TOPP is pioneering the application of biologging science to study pelagic habitat use by marine vertebrates and large squid in the North Pacific. The program has four primary long-term goals. First, develop methods and equipment necessary to implement large-scale, multi-institutional, multi-species electronic tagging programs. Second, improve basic knowledge of oceans, species and key processes linking apex predators to their ocean environs. Third, integrate environmental data collected by the tagged animals into global oceanographic databases for use in ocean observation, model testing and development. Fourth, build an education and outreach program that will educate the public about the marine environment and associated conservation issues.

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